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FINITE ELEMENT ANALYSIS OF STRESSES, DEFORMATIONS AND PROGRESSIVE FAILURE OF *NON*-HOMOGENEOUS FISSURED ROCK

VOLUME 3: COMPUTER PROGRAMS

OHIO STATE UNIVERSITY

PREPARED FOR
ADVANCED RESEARCH PROJECTS AGENCY

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STRESSES, DEFORMATIONS AND PROGRESSIVE FAILURE OF NON-HOMOGENEOUS FISSURED ROCK

Final Report
Volume 3 — Computer Programs
March 1973

U.S. BUREAU OF MINES
Contract Number HO210017

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ADVANCED RESEARCH PROJECTS AGENCY
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Program Code 1F10

Principal Investigators

R. S. Sandhu
T. H. Wu
J. R. Hooper

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THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION
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13. ABSTRACT

The objective of this research program was development of finite element procedures for prediction of stresses and deformations in the vicinity of underground excavation.

Two models of rock behavior were selected. In one the rock is treated as isotropic elastic-plastic following a generalized Mohr-Coulomb law and in the other the rock is isotropic elastic-brittle subject to Griffith or modified Griffith failure theory.

For each model, mathematical relationships governing stress-strain behavior and progressive failure were developed. Finite element computer programs incorporating each of the two models were coded. Preliminary to this development, a revised version of Zienkiewicz's no-tension analysis was programmed.

The procedures developed allow for initial stresses in rock, arbitrary shape and size of the opening, any given sequence of construction/excavation, material nonhomogeneity and progressive failure.

This report is in three parts: Volume 1-Main Document; Volume 2-Computer Program User's Manual; Volume 3-Computer Programs

Volume 3 -Computer Programs, contains the layout sheet relating to computer programs used to obtain the numerical results presented and discussed in Volume 1-Main Document.

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FINAL REPORT

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Principal Investigators: R. S. Sandhu
T. H. Wu
J. R. Hooper

Telephone Number: (614) 422-7531

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TABLE OF CONTENTS

FOREWORD

The final report on work done under contract HO210017 between the Ohio State University and the United States Bureau of Mines is in three parts as follows:

Volume 1:	Main Document
Volume 2:	Computer Program User's Manual
Volume 3:	Computer Programs

Volume 3 of the report consists primarily of the three computer programs developed under this research project. These programs are on magnetic tape available from DDC-TC, United States Department of Commerce, Springfield, Virginia, 22157.

It is obvious that these computer programs be used only under the conditions and assumptions for which they were developed. These are described in Volume 1 of this report. Although the programs have been tested by applications to several problems, no warranty is made regarding the accuracy and reliability of the programs and no responsibility is assumed by the authors or by the sponsors of this research project.

The technical report summary is included in all three volumes of the report.

R.S. Sandhu
Principal Investigator

TECHNICAL REPORT SUMMARY

Program Objectives

The objective of this research program was development of finite element procedures to predict stresses, deformations and progressive failure of rock associated with underground excavations. For applicability to arbitrary sequence of excavation operations, it was necessary that the procedures developed allow for arbitrary initial stresses in rock, arbitrary size and shape of the opening and progressive failure. Plane strain conditions and two different types of material behavior were considered. Rock was treated as an isotropic elastic-plastic generalized Mohr-Coulomb material in one model and as an elastic-brittle material following Griffith theory of fracture in the other.

Background

In previous applications of the finite element method to rock mechanics, elastic-plastic behavior of rock has been modeled as nonlinear elastic for computational convenience. Further, it was assumed that the results of a one-dimensional test could be generalized to three-dimensional analysis through the use of an equivalent stress-equivalent strain curve. In some applications, two stress or strain parameters were used. These procedures are unsatisfactory. Assumption of isotropic elasticity assumes that the principal directions of stress and strain coincide. In plasticity this is not true. Also, rock behavior is characterized by a significant part of deformation being irreversible. For this reason, the mechanical behavior in unloading is different from that in loading. For rock with preexisting joints or developing tensile cracks, a 'no tension'

procedure is often adopted. In this method, a linear elastic solution is obtained and all tensile stress redistributed simultaneously. Actually, as cracking progresses, the rock on either side of the crack is relieved of stress and a stress concentration develops near the crack tip. Conventional procedures ignore these effects and the progressive nature of crack development, leading to erroneous conclusions regarding stresses around underground openings.

Accomplishments Under the Present Program

The research conducted under this contract has resulted in development of computer programs based on more realistic simulation of material behavior. The incremental theory of plasticity has been used to characterize the stress-strain behavior of elastic-plastic rock. Role of kinematic constraint of plane strain in development of residual stresses in rock has been examined on the basis of Hill's theory. New techniques have been developed for study of initiation and propagation of fracture in rock following Griffith's theory or the modified Griffith theory. Allowing for sequential fracture of various elements in a system, the effect of progressive stress redistribution in the remaining system is correctly incorporated. Arbitrary initial stress states, arbitrary sequence of excavation (or construction), arbitrary size and shape of opening, and nonhomogeneous material properties were allowed for. The actual construction operations can be simulated. The procedures developed were applied to several typical problems in rock mechanics as well as to some theoretical and laboratory studies for the purpose of verification and illustration. These were used to carry out parametric studies to examine the influence of rock properties upon the stresses in steel supports in a tunnel.

DOD Implications

The procedures developed provide useful means for study of stability of underground excavations based on stresses and deformations associated with the mining operations, structural support evaluation, safety analyses of openings, study of blasting effectiveness under certain conditions, evaluation of mining sequences, study of vulnerability and serviceability of underground structures etc.

Organization of the Report

This report is in three parts as follows:

Volume 1 - Main Document
Volume 2 - Computer Program User's Manual
Volume 3 - Computer Programs

Volume 1 contains the main body of the report including the theoretical development, program verification and case studies. Chapter I reviews previous efforts in the general research area and describes the objectives and methods of the present research in the historical context. Chapter II describes the mechanical behavior of rock and the idealizations used in the research under report. The basis and methods of the finite element theory are briefly discussed in Chapter III leading to the formulation of matix equations. Chapter IV gives details of the analysis technique for isotropic elastic-plastic generalized Mohr-Coulomb rock materials and Chapter V gives the numerical analysis procedure for jointed rock and rock subjected to progressive fracture following Griffith or modified Griffith theory. Examples of application are included in Chapters IV and V. Chapter VI presents application of the elastic-plastic analysis computer program to a parametric study to evaluate the influence of rock properties on stresses in steel supports for specified initial stresses and design of the opening.

In the original proposal, model testing to verify some aspects of rock behavior under plane strain conditions was foreseen. The effort under the present contract covered procurement of suitable plane strain test equipment and design of suitable test material. Appendix B includes a report on this effort.

Volume 2 of the report contains description of the three computer programs developed under the contract along with fortran listings and instructions for input preparation. The input definition and the listings are for the IBM 370/165 version.

The programs are the primary content of volume 3. These are available on magnetic tape from DDC-TC, U.S. Department of Commerce, Springfield, Virginia 22151, telephone (703) 321-8517.

ACKNOWLEDGEMENTS

The research was supported by the U.S. Government through the Advanced Research Projects Agency, ARPA, and its agent the U.S. Bureau of Mines, Department of the Interior. James J. Olson, Twin Cities Mining Research Center, was the ARPA program coordinator and Dr. William J. Karwoski, Spokane Mining Research Center, was the Project Officer. In early stages of work. Dr. Syd Peng, Twin Cities Mining Research Center acted as the Project Officer. Constant cooperation and several constructive suggestions from these individuals are gratefully appreciated.

A number of graduate students worked on the project. The contributions of Messrs. Ram Dhan Singh, S. W. Huang and Kamar Jit Singh were specially noteworthy. The Instruction and Research Computer Center of the Ohio State University provided the computational facilities.

R. S. Sandhu
Project Supervisor

LAYOUT SHEET

This layout sheet pertains to the magnetic tape on which the three computer programs developed under this research project are stored.

The following applicable data appear on the label with the tape:

Report No.: OSURF-3177-73-3F
Date of file: 3/31/73
Density of file: 800 characters/inch
Reel No.: 1 of 1
Title: OSURF1
File 1: Program NOTENS
File 2: Program ELPL
File 3: Program PFA

The programs NOTENS and ELPL use scratch files 1,2 referred to as tapes 1,2. In addition, all the three programs use tapes 5 and 6 as input/output files respectively.